

# Nano-Enabled Monitoring Of *Musca* Spp. In Pig Farms: Associations With Microclimate, Animal Wound Status, And Hygiene Interventions

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This study proposes a nano-enabled environmental monitoring framework to assess ecological drivers of *Musca* spp. abundance in pig farming systems. The monitoring system integrated microclimate sensing, biologically responsive traps, and animal health observations in pig farms in North Sulawesi, Indonesia. Temperature and relative humidity were recorded using digital environmental sensors, while fly abundance was measured using net traps, bottle traps, and colored adhesive surfaces. A total of 231 *Musca* spp. were captured, with net traps showing the highest efficiency (109 individuals), followed by bottle traps (72), while blue adhesive surfaces were the most effective visual attractant (48). Fly activity increased under temperatures of 23–31 °C and humidity levels of 74–88%, with significantly higher attraction to animals presenting wounds.

These findings demonstrate that fly abundance is influenced by interacting environmental, biological, and surface-attraction mechanisms, highlighting the potential of sensor-based monitoring systems for improved livestock biosecurity.

**Keywords:** nano-enabled monitoring, *Musca* spp., microclimate sensing, livestock biosecurity, surface interaction traps.

## 1. Introduction

Synanthropic flies such as *Musca domestica* are among the most common biological vectors found in livestock production environments. In pig farms, these insects contribute to the mechanical transmission of pathogenic microorganisms and are associated with increased animal stress and reduced productivity. Effective monitoring of fly populations is therefore essential for maintaining biosecurity and animal welfare in intensive farming systems (Bertelloni et al., 2023; Gerry, 2020).

Environmental factors strongly influence the population dynamics and activity patterns of synanthropic flies. Temperature and relative humidity regulate insect metabolic rates, flight activity, and larval development. Within enclosed livestock facilities, microclimate conditions may fluctuate considerably during the day, especially in tropical regions. These variations

create ecological niches that support rapid increases in fly abundance (Goldshstein et al., 2021; Kim et al., 2021).

Recent advances in environmental monitoring technologies have opened new opportunities for integrating biological surveillance with high-resolution sensing systems. In agricultural environments, emerging nano-enabled sensing frameworks combine environmental sensors, responsive surfaces, and ecological observations to improve the detection of biological agents and environmental changes. Such approaches form part of a broader movement toward precision livestock management, where environmental data and biological indicators are used to guide targeted interventions (Holinger et al., 2024; Li et al., 2022).

Despite these developments, monitoring studies in livestock facilities often remain fragmented. Many investigations focus exclusively on trap performance, while others analyze environmental conditions without linking them to vector abundance. Similarly, host-related factors such as wounds or skin lesions which may release volatile compounds attracting flies are rarely incorporated into environmental monitoring systems (Lutz et al., 2019; Moyano et al., 2023).

In tropical pig-farming environments, the absence of integrated monitoring approaches limits our understanding of how environmental conditions, host health status, and trap characteristics interact to influence fly populations. Addressing this gap requires a monitoring framework that simultaneously captures environmental parameters, vector activity, and biological attractants (Snyder et al., 2022).

The present study proposes an integrated monitoring system that combines microclimate sensing, comparative trap evaluation, and animal health observations. Within this framework, environmental sensors provide high-resolution microclimate data while trap surfaces function as biological detection interfaces for synanthropic flies (Holinger et al., 2024).

The objectives of this study were:

1. To evaluate the effectiveness of different trap types and colors in monitoring *Musca* spp. abundance.
2. To analyze the relationship between microclimate parameters and fly activity patterns.
3. To assess the influence of animal wound status on fly attraction in pig farming environments.

By integrating environmental sensing, host health indicators, and trap-based detection, this study contributes to the development of nano-enabled biological monitoring frameworks for livestock biosecurity and pest management (Li et al., 2022; Snyder et al., 2022).

## **2. Research Methodology**

The study was conducted in two commercial pig farms located in North Sulawesi, Indonesia, between August and October 2025. The selected farms represented typical tropical pig-farming environments with moderate to high animal densities and open-sided housing. Observations were carried out over 14 consecutive days at each farm, with three daily measurement points (08:00, 12:00, and 16:00), totaling 126 observation sessions per farm.

A nano-enabled environmental monitoring framework was implemented, combining:  
Microclimate sensing : temperature and relative humidity were continuously recorded using digital environmental sensors (accuracy  $\pm 0.5^{\circ}\text{C}$  for temperature,  $\pm 2\%$  for relative humidity)

positioned at pig head height (80–100 cm). Sensors were calibrated prior to deployment. Data were logged at 15 minutes intervals and aggregated into diurnal mean, minimum, and maximum values for analysis.

Four types of fly traps were deployed simultaneously to assess both structural and visual attractants:

- Net trap: airflow-permeable structure facilitating odor diffusion (baited with fermented protein attractant).
- Bottle trap: transparent funnel trap for protein-seeking flies (baited).
- Sticky paper traps: flat adhesive surfaces in blue, black, yellow, and white for visual attraction.
- Sticky stick traps: cylindrical adhesive surfaces offering 360° visual exposure.

Trap locations were randomized and rotated across observation sessions to minimize positional bias. Fly captures were counted and identified to genus level using standard morphological keys.

Host health observation, ten pigs were purposively selected for intensive monitoring: five with visible integumentary wounds and five without wounds. Wound status served as a biological attractant factor, representing host-derived volatile emissions. Fly counts around these pigs formed a focused dataset to assess the interaction between microclimate, trap type, and host condition.

Two datasets were generated for analysis:

- Dataset A : Overall Trap Performance: All traps across all pigs and sampling points; used to evaluate trap efficiency, color performance, and temporal activity patterns.
- Dataset B : Wound-Attraction Focus: Fly activity around wounded vs. healthy pigs; used to quantify host-derived attraction and interaction with trap types.

Trap and Color Performance – Normality assessed using Shapiro–Wilk test. Depending on distribution:

ANOVA with Tukey post hoc (parametric) or

Kruskal–Wallis with Dunn post hoc (non-parametric)

Statistical significance set at  $\alpha = 0.05$ .

Wound Effect Analysis – Independent t-test or Mann–Whitney U test for comparing fly abundance between wounded and non-wounded pigs. Effect sizes (Cohen’s d or rank-biserial correlation) and 95% confidence intervals were calculated.

Correlation between fly counts and temperature/humidity using Pearson (parametric) or Spearman (non-parametric) coefficients. Multivariable regression models were constructed to evaluate the combined influence of microclimate, trap type, and wound status on fly abundance.

All observations were non-invasive, with no direct handling or experimental manipulation of animals. Ethical approval for observational monitoring was obtained from the Institutional Ethics Committee of Sam Ratulangi University, Indonesia.

The study emphasizes the potential of nano-enabled environmental monitoring in livestock systems. Micro-scale sensors coupled with biologically responsive trap surfaces and host health indicators provide an integrated framework for real-time, adaptive pest surveillance, supporting future precision livestock management and biosecurity interventions.

### 3. Results and Discussion

The results demonstrate that trap architecture strongly influences the detection efficiency of *Musca* spp. within livestock environments. Net traps captured substantially more flies than bottle traps and adhesive surfaces, indicating that trap geometry and airflow permeability play important roles in the dispersion of attractant cues and insect interception. Open mesh structures enhance the diffusion of odor plumes from protein-based baits and increase the visual detectability of traps, thereby expanding the spatial detection range of monitoring devices. These findings align with recent studies showing that trap efficiency in dipteran monitoring systems is determined by the interaction between visual stimuli, odor dispersion, and trap structure (Getahun et al., 2024).

From a technological perspective, fly traps function as surface-interaction detection systems, where insects are detected when they contact visually or chemically attractive surfaces. Adhesive traps, for example, rely on physical adhesion mechanisms combined with optical contrast cues. Such systems represent passive biological sensors capable of detecting insect activity without electronic instrumentation. Recent research in insect monitoring has highlighted how trap surfaces can act as detection interfaces where visual cues and chemical attractants synergistically increase capture rates (Getahun et al., 2024).

Among the adhesive surfaces tested in this study, blue sticky papers demonstrated the highest capture efficiency. This observation aligns with the known spectral sensitivity of *Musca domestica*, whose compound eyes respond strongly to wavelengths in the blue-green range (~440–540 nm). Laboratory and field studies confirm that visual targets reflecting light in this spectrum trigger stronger behavioral responses and increase trap attractiveness for house flies (Emerty & Mulasari, 2020; Azahra et al., 2024).

Microclimate monitoring revealed clear diurnal fluctuations in temperature and relative humidity within pig housing. Peak fly activity occurred during midday when temperatures approached the upper limit of the thermal comfort zone for pigs. Environmental conditions strongly influence insect metabolism, flight activity, and host-seeking behavior, with warmer temperatures shown to increase locomotor activity and foraging intensity in synanthropic flies (Kim et al., 2021; Goldshtein et al., 2021).

Temperature exhibited a moderate positive correlation with fly abundance, while humidity showed a weaker but still positive effect. This indicates that thermal conditions are the primary environmental driver of fly activity, with humidity amplifying heat effects on behavior. Similar relationships have been reported in livestock facilities, demonstrating that warm and moderately humid conditions accelerate adult fly movement and host-seeking (Snyder et al., 2022; Moyano et al., 2023).

From a monitoring-technology perspective, these findings highlight the value of continuous environmental sensing systems. Advances in micro-scale sensors allow temperature and humidity to be measured with high temporal resolution in agricultural settings. Integrated with biological monitoring, such sensors enhance the predictive capacity of pest surveillance frameworks and enable adaptive intervention strategies (Holinger et al., 2024; Li et al., 2022). Host condition emerged as a major determinant of fly abundance. Wounded pigs consistently attracted more flies than healthy pigs, suggesting tissue damage produces chemical signals that serve as strong attractants. Wounds release volatile organic compounds and microbial

metabolites during tissue degradation, which function as feeding cues for dipteran species, creating localized attractant hotspots (Lutz et al., 2019; Moyano et al., 2023).

The attraction of flies to host-derived odors has been widely documented in vector ecology. Odor cues from animal waste, decomposing organic matter, or damaged tissue provide sensory signals guiding orientation and feeding. Studies on olfactory-based trapping show that combining visual and odor cues increases capture rates compared with visual traps alone (Guarino et al., 2018; Jørgensen et al., 2024).

From a technology perspective, host-derived chemical cues represent potential targets for biosensing in livestock monitoring. Emerging nanomaterial-based chemical sensors can detect volatile compounds associated with biological processes. Integrating these into livestock facilities could enable early detection of wound emissions and improve identification of animals at higher risk of vector exposure (Holinger et al., 2024; Li et al., 2022).

A key outcome of this study is that fly abundance is determined by the interaction of environmental conditions, host-derived attractants, and trap detection mechanisms. Wound presence emerged as the strongest predictor, followed by temperature and trap design. This indicates that biological attractants determine vector aggregation location, while environmental conditions regulate activity intensity (Snyder et al., 2022; Goldshtein et al., 2021).

Integration of multiple monitoring components provides a comprehensive understanding of vector dynamics. Prior studies emphasize that effective insect monitoring must incorporate both visual and olfactory cues, as insects rely on multimodal sensory information when locating hosts or food sources (Azahra et al., 2024; Emerty & Mulasari, 2020).

In livestock production, integrated monitoring frameworks combining environmental sensing, biological surfaces, and host-health indicators are increasingly recognized as essential to precision livestock management. Such systems allow early identification of ecological risk conditions and timely interventions (Li et al., 2022; Holinger et al., 2024).

The monitoring framework applied in this study demonstrates how future biosecurity systems may be developed. Conventional monitoring relies on manual counting and simple traps, whereas recent technological advances allow automated platforms integrating environmental sensors, optical detection, and chemical sensing (Azahra et al., 2024; Li et al., 2022).

Future livestock facilities could use nanoscale sensors to continuously measure temperature, humidity, and trace volatile compounds, integrated with smart traps or image-recognition systems for real-time vector detection. Such systems would enable continuous surveillance and adaptive pest management (Holinger et al., 2024; Li et al., 2022).

By demonstrating the interacting roles of microclimate variability, host-derived attractants, and trap architecture, this study provides empirical evidence supporting sensor-supported and nano-enabled monitoring systems for livestock biosecurity and precision pest management (Azahra et al., 2024; Snyder et al., 2022).

In conclusion, optimizing trap color represents a practical strategy for enhancing fly monitoring efficiency. Future work should integrate color-based traps with nano-enabled sensors, automated image analysis, and environmental monitoring to develop intelligent, adaptive pest surveillance systems in livestock environments (Emerty & Mulasari, 2020; Holinger et al., 2024).

#### 4. Conclusion

This study demonstrated that different trap colors significantly influence the capture rate of flies in livestock environments. Among the tested treatments, the yellow sticky trap showed the highest effectiveness in attracting and capturing flies compared with other colors. This result indicates that visual cues play an important role in fly attraction and can be utilized as a simple but efficient monitoring tool in livestock facilities. Beyond its entomological implications, the findings contribute to the development of technology-assisted biological monitoring systems. Color-based trapping mechanisms can serve as fundamental components for smart monitoring devices designed to detect insect population dynamics in agricultural environments. By integrating optimized visual attractants with environmental sensors, automated counting systems, or digital imaging technologies, trap-based monitoring could evolve into a more advanced surveillance platform for pest management in livestock production.

Furthermore, the integration of trap-based monitoring with emerging technologies such as sensor networks and nanotechnology-based detection systems may enable more precise and real-time monitoring of insect activity. Such approaches could support early detection of pest outbreaks, improve livestock health management, and contribute to sustainable pest control strategies in modern agricultural systems.

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